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Abstract

Hazardous materials are potentially harmful to people and environment due to their toxic ingredients. Although significant portion of dangerous goods transportation is via railroads, prevailing studies on dangerous goods transport focus on highway shipments. We present an analytical framework that incorporates the differentiating features of trains, notably volume and nature of cargo, in the assessment of transport risk. We focus on hazardous materials that are airborne upon an accidental release into the environment. Each railcar is a potential source of release, and hence risk assessment of trains requires representation of multiple release sources in the model. We propose a novel railcar referencing and risk approximation approach, which is not only effective but also robust with regards to the positioning of hazardous railcars in the train. We report on implementation of the proposed approach for assessment of the population exposure associated with "Ultra-train" that passes through the city of Montreal everyday.

Key words: hazardous materials, railroad shipments, risk assessment, Gaussian plume model.

Résumé

Les matières dangereuses sont potentiellement nuisibles à la population et à l'environnement en raison de leurs ingrédients toxiques. Bien qu'une portion significative des matières dangereuses soit transportée par rail, les études prédominantes sur le transport des matières dangereuses traitent des chargements routiers. Nous présentons un cadre analytique qui incorpore les aspects différenciateurs des trains, en particulier le volume et la nature de la cargaison, dans l'évaluation du risque du transport. Nous concentrons notre recherche sur les matières dangereuses qui sont transportées par voie aérienne lors d'une émission accidentelle dans le milieu environnant. Parce que chaque wagon est une source potentielle d'émissions, l'évaluation du risque requiert la représentation de sources multiples d'émission dans le modèle. Nous proposons un nouveau système de références des wagons et une approche originale de l'approximation du risque qui sont non seulement efficaces mais aussi robustes en ce qui concerne la position dans le train des wagons transportant des matières dangereuses. Nous appliquons l'approche proposée pour évaluer l'exposition de la population reliée à l'«Ultratrain » qui traverse la ville de Montréal chaque jour.

Mots clés : matières dangereuses, chargements de chemin de fer, évaluation du risque, modèle gaussien de dispersion.

1. Introduction

In industrial societies vast amounts of hazardous materials (hazmats) are being shipped from their points of origin, such as refineries and chemical plants, to their points of consumption, such as manufacturing facilities, gas stations and homes. For example, the daily number of dangerous goods shipments in the U.S. through roads, railways, pipelines, waterways and air amounts to well over 800,000 [1]. Mitigation of the public and environmental risks associated with these shipments has become a popular concern. Prevailing literature reviews show that an overwhelming majority of the research on hazmat transportation focuses on road shipments (List et al. [2] and Erkut and Verter [3]). Although trucking companies do carry a larger share of dangerous goods shipments in many countries, railroad shipments can easily reach comparable levels. In Canada, for example, 48 million tons of hazardous freight was carried via rail while 64 million tons was shipped via trucks in 2000 [4]. Consequently, there is a need for development of risk assessment methodologies that incorporate the specific nature of railroad shipments, which we address in this paper.

There are a number of factors that differentiate rail transport from truck shipments. A train usually carries non-hazardous and hazardous cargo together, whereas these two types of cargo are almost never mixed in a truck shipment. A rail tank-car has roughly three times the capacity of a truck-tanker (80 tons and 25-30 tons respectively) and the number of hazmat railcars varies significantly among different trains. The resulting variability in the total amount of hazardous cargo needs to be taken into account in assessing the transport risk associated with trains. In the event of an accident more than one railcar can be ruptured simultaneously or a fire in one of the railcars can easily lead to a larger fire involving multiple railcars. Therefore, train risk assessment models need to represent multiple sources of release in estimating the potential undesirable consequences. Empirical evidence suggests that trains have lower accident rates than trucks (Saccomanno et al. [5]). Train accidents, however, can have much worse consequences due to the higher amounts of hazmats involved and the interaction between railcars. A well-known example is the 1979 accident in Mississauga, Ontario, where a train carrying toxic chemicals was derailed and chlorine leaking from damaged tank cars forced the evacuation of 200,000 people (Swoveland [6]).

Traditionally, the *impact area* of an incident is assumed to be a circle centered at the incident location and it is called the danger circle (Batta and Chiu [7]). The radius of a danger circle depends on the type of hazmat being shipped. For example, according to the North American Emergency Response Handbook [8], 800 meters around a fire that involves a chlorine tank, railcar or tank-truck must be isolated and evacuated. The implicit assumption is that only the people within the pre-defined *threshold distance* from the incident site are exposed to hazmat transport risk It is possible to consider the hazmat shipment over a transport link as the movement of the danger circle along that link. This movement carves out a band (on both sides of the link) that is called the exposure zone (ReVelle et al. [9]). Although this fixed bandwidth approach is practical for initial emergency response, it ignores the impact of released hazmat volume and weather conditions in determining the possible undesirable consequences. Thus, the traditional approach can grossly underestimate transport risk, particularly in the case of trains.

In this paper, we focus on railroad transportation of hazmats that become airborne in the event of an accidental release, such as chlorine and ammonia. In contrast with incidents where undesirable consequences are confined to the vicinity of accident site, airborne contaminants can travel long distances due to wind and expose large areas to health and environmental risks. We use the Gaussian plume model in estimating spatial distribution of the toxic concentration level. Concentration increases with release rate of hazmat, whereas it decreases with distance from the accident site and wind speed. At a given distance from a release source, the maximum concentration is observed at the downwind location. We use the Immediately Dangerous to Life and Health (IDLH) [10] concentrate levels of the hazmat being shipped in determining the threshold distances for fatality and injuries. Thus, in our model, the impact area around the accident site depends on the type and volume of hazmat released. We adopt a worst-case approach to risk by assuming least favorable weather conditions and focusing on maximum concentrate levels. The model captures the multiple release source nature of train accidents via a novel railcar referencing procedure. Since exact calculation of transport risk associated with railroad shipments proves to be quite cumbersome, we also present an approximation procedure that is effective and robust to train make-up[1].

[1] Train make-up refers to the length of train as well as the type and positioning of its cargo.

Although a large number of researchers studied railroad transportation (see Cordeau et al. [11] for a comprehensive survey), the literature on the use of trains for dangerous goods shipments is sparse. Early work on railroad shipments focused on the impact of spills within one mile around the accident site. Analyzing past data on train derailments, Glickman and Rosenfield [12] derived and evaluated three forms of risk. These are probability of the number of fatalities in a single accident, probability of the total number of fatalities from all the accidents in a year, and frequency of accidents which result in any given number of fatalities. Glickman [13] showed that rerouting of trains with (or without) track upgrades can reduce risk. The trade-off between the societal and individual risks of hazmat shipments is addressed in Saccomanno and Shortreed [14]. More recent work focused on the comparison of rail and road shipments in terms of transport risk. Glickman [15] concluded that the accident rate for significant spills (when release quantities exceed 5 gallons or 40 pounds) is higher for for-hire truck tankers compared to rail tank cars, whereas rail tank cars are more prone to small spills. Saccomanno et al. [5] pointed out that differing volumes complicate comparison between the two transport modes, and showed that the safer mode varies with the hazmat being shipped.

The remainder of this paper is organized as follows: Section 2 describes the use of a Gaussian plume model for assessment of railroad transport risk, and Section 3 discusses the insights provided by the model. Section 4 presents our approximation approach, whereas Section 5 reports on an application of the proposed methodology in the province of Quebec, Canada. Finally, Section 6 provides some concluding comments.

2. Risk Assessment Framework for Railroad Shipments

In this paper, we use population exposure in representing transport risk. The use of a fixed bandwidth approach, that implicitly assumes a standard hazmat volume, is inappropriate for estimating the number of people put at risk due to railroad shipments. The number and location of railcars with hazardous cargo vary considerably among trains. Consequently, it is important to define the boundary of impact area as a function of the volume of hazmat being shipped. A train including one propane tank-car exposes an individual living 1 kilometer from the railroad to minor injury risk, whereas the same individual would be exposed to fatality risk due to a train with 21 propane tank-cars. This can be explained by the considerable increase in the toxic concentration level at the individual's location due to the additional railcars. We

define exposure in terms of the level of toxic material concentration, which we estimate via the Gaussian plume model. We consider an individual "exposed" to a certain undesirable consequence, if the imposed toxicity level is at (or higher than) the associated IDLH level.

The risk of airborne hazmats due to a *single* release-source, such as a truck tank-car, has been studied by the use of Gaussian plume model [16], [17]. The Gaussian plume model is also used by micro-meteorologists, air pollution analysts, and regulatory agencies [18], [19]. We first adapt the standard model to represent a single railcar. Then, we extend the model to represent train shipments, which typically involve multiple release-sources. Assuming that the release-source and the impact point are at zero elevation, our single railcar model is as follows:

$$C(x,y) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left(-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right) \qquad (1)$$

where,

$C(x,y)$ concentration level (ppm) at impact point (x,y) in *steady-state*

Q the release rate of pollutant (mg/sec)

u average wind-speed (meters/sec)

s_y horizontal dispersion coefficient (meters), $s_y = ax^b$

s_z vertical dispersion coefficient (meters), $s_z = cx^d$

x downwind distance from the source (meters)

y crosswind (perpendicular) distance from the source (meters).

In estimating the steady state concentration level at point (x,y), the model assumes that the release rate and atmospheric conditions remain constant over the period of dispersion. The release rate, Q, depends on container volume, hazmat type and rupture diameter. We use ALOHA [19], a popular software among North American regulatory agencies including EPA, DoT and Transport Canada, to calculate the release rate[2]. We assume a 24-inch rupture at the bottom of the railcar, which typically results in the highest release rate. Dispersion coefficients s_y and s_z are determined by atmospheric stability category and the downwind distance, x, to the release source. Pasquill and Smith [20] provide the values of dispersion parameters a, b, c and

[2] Although ALOHA can also be used for estimating the concentration level, $C(x,y)$, its results are only reliable within 1 hour of the release event, and 10 kilometers from the release source.

d based on atmospheric stability category. Each atmospheric category is determined by a combination of factors such as solar radiation, cloud-cover, and humidity. Each atmospheric category is compatible with a range of wind-speeds. In order to estimate worst-case conditions, we focus on the minimum possible wind-speed, 2.5 meters/sec., under neutral atmospheric conditions i.e., stability category D. At a given (Euclidean) distance from the release source, the maximum concentration level is observed at the downwind point i.e., when crosswind distance $y=0$. Thus, the maximum concentrate level at (downwind) distance, x, from a release source is

$$C(x) = \frac{Q}{\pi u \sigma_y \sigma_z} \qquad (2)$$

The two shaded areas in Figure 1 depict typical footprints of the Gaussian plume from a single release source, when the wind is blowing east. Each footprint represents the area where toxicity is higher than a pre-specified concentration level e.g., the IDLH level associated with a certain undesirable consequence. The inner footprint corresponds to higher exposure to hazmat transport risk. One way to address the uncertainty in wind direction is by rotating the footprint around the release source, which constructs a circle. Consequently, the furthest point from the release source, where threshold concentration level is attained, defines radius of the circle (e.g., point P in Figure 1). This constitutes a worst-case approach to transport risk, since the concentrate level at any point on the circle cannot be higher under any plausible wind direction. The two concentric circles in Figure 1 represent, for example, severe and non-severe impact areas under wind direction uncertainty. Note that, in contrast with traditional approach, the radius of each impact area varies with the release rate.

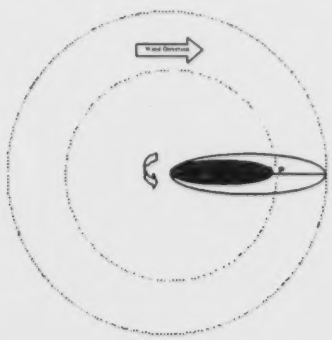

Figure 1: Two footprints of a Gaussian plume and the associated danger circles

Patel and Horowitz [16] were the first to use the Gaussian plume model, coupled with a geographical information system (GIS), for hazmat transport risk assessment. In an effort to develop closed-form expressions, they assumed that dispersion parameters b and d are equal to one. They developed a numerical method to determine the minimum risk path under four scenarios: specific wind direction, uniform average wind direction, maximum concentration wind direction and wind-rose averaged wind directions and speeds. Patel and Horowitz [16] represented risk as the total expected contaminant concentration due to a potential spill. Recently, Zhang et al. [17] modeled the probability of an undesirable consequence as a function of the concentration level, and used the traditional expected consequence representation of transport risk. They adopted a raster GIS framework that approximates the plane with a set of discrete points i.e., pixels. This enabled the authors to compute the concentrate levels without having to make the linearity assumption as in [16] that essentially ignores atmospheric stability conditions. The method proposed in [17], however, assumes a pre-specified wind direction and speed.

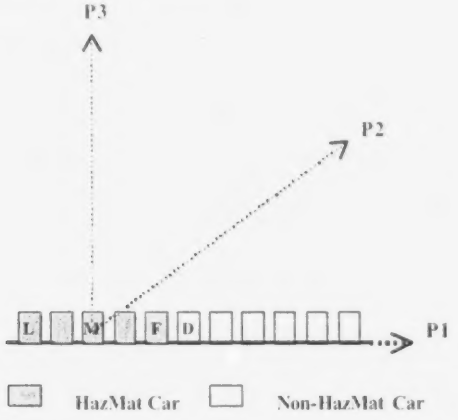

Figure 2: Schematic representation of an 11-railcar train

Now, we extend the basic Gaussian plume model to incorporate multiple release-sources.. In Figure 2, assuming that the 11-railcar train is travelling east, F and L denote the first and last railcars with hazardous cargo, respectively. M is the point with equal amount of hazmats on both sides, which we call *hazmat-middle* of the train[3]. Note that M and D, the middle of the

[3] If there is an even number of hazmat railcars, then M is midpoint of the two hazmat railcars at the center of hazardous cargo.

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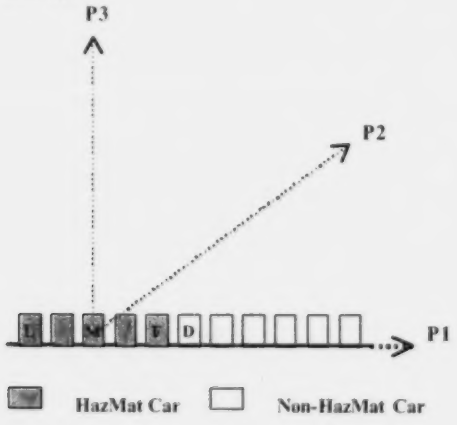

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train, do not necessarily refer to the same point. *P1*, *P2* and *P3* are equidistant from *M*. In Figure 2, the five hazmat railcars are *blocked* at the back of the train.

Pasquill and Smith [20] suggested that pollution from an array of sources with an arbitrary distribution of position and strength of emission can be modeled by superposing the patterns of pollution from these sources, and hence aggregating the resulting contamination at each impact point. In Figure 2, when the wind is blowing east, *P1* constitutes a downwind location where crosswind distance $y=0$ for all railcars. In the event of a major incident that ruptures all five railcars with hazardous cargo, the total concentrate level at *P1* would be sum of the concentrate levels associated with each railcar, which can be estimated via (2). We assume the same (worst case) release rate for each railcar. The three curves in Figure 3 depict total concentration at *P1* as a function of distance to *F*, *M*, and *L*, respectively. Consider a fixed reference point at $x=0$. As the train travels east, *F*, *M*, and then *L* pass by the reference point. Thus, Figure 3 also shows the upward shift in concentrate level as a result of the train's movement. Note that contaminant toxicity increases much faster at impact points closer to the train.

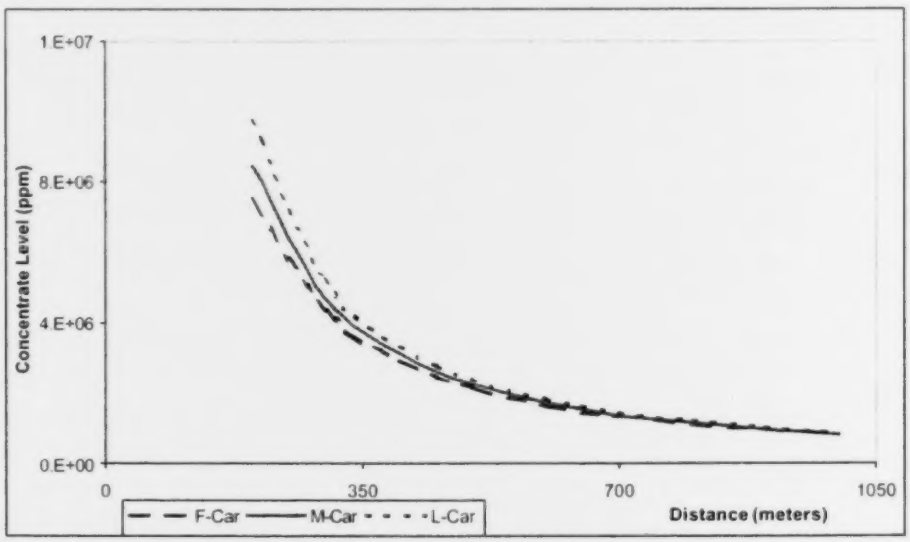

Figure 3: Impact of a 5 tank-car propane block

When the wind is blowing northeast in Figure 2, *P2* is downwind from *M* and it has positive crosswind distances (i.e., $y>0$) to the other four railcars. Therefore, the maximum concentration at *P2* cannot exceed that of *P1*. Similarly, the maximum concentration at *P3*,

which is attained when the wind is blowing north, is less than that of P1. Thus, *P1* is the *maximum concentration point* among all the locations equidistant from *M*. When the distance from hazmat-middle of an 11-railcar propane block is 1,500 meters, for example, the concentrate levels at *P2* and *P3* are *95.8%* and *95.5%*, of the maximum level, respectively. This difference decreases with distance and increases with the number of hazmat railcars.

In accordance with the worst-case approach to transport risk, we focus on the maximum concentration level that can be reached at a given distance irrespective of the wind direction. Analogous to the single release-source case, it is possible to construct a danger circle around the train by rotating the maximum concentration point, *P1*, around the hazmat-middle, *M*. Therefore, we use the hazmat-middle as the *reference point* for the train. This assures consistency among the maximum concentrate levels under opposite wind directions, when hazmat railcars are blocked. If another point were used as reference, the concentrate levels at the opposite downwind locations from the hazmat railcar block would be different. Take, for example, *F* as an alternative reference point. Since all the railcars are behind *F*, the total concentrate level at a certain downwind distance will be higher when the train is moving upwind. Because the amount of hazardous cargo on both sides of *M* is the same, it constitutes the best option for a reference point.

Thus, the maximum concentrate level at distance x from the hazmat-middle of an n-railcar hazmat block is

$$C_n(x) = \frac{Q}{\pi\ u\ a\ c\ x^b x^d} + \frac{Q}{\pi\ u\ a\ c\ (x-l)^b (x-l)^d} + \frac{Q}{\pi\ u\ a\ c\ (x+l)^b (x+l)^d} + \cdots\cdots\cdots + \frac{Q}{\pi\ u\ a\ c\ (x-nl/2)^b (x-nl/2)^d} + \frac{Q}{\pi\ u\ a\ c\ (x+nl/2)^b (x+nl/2)^d} \qquad (3)$$

where, l denotes the length of each railcar. In the next Section, we present a number of insights obtained via the above model. Computing (3) becomes increasingly tedious as n, the number of railcars with hazardous cargo, increases. Thus, we provide an approximate method for calculating the maximum concentrate level in Section 4.

3. The Nature of Railroad Transport Risk

Using (3), we analyze the independence between train make-up and threshold distance. We first address the question "How does the impact area vary with the positioning of a given number of hazmat railcars in the train?" The following comparison between two alternative configurations of a 68-railcar train that includes 20 tank-cars of propane provides some insight. In Figure 4, "20 Cars" represents the concentration curve associated with a block of 20 propane tank-cars at the center of the train, whereas "20 Cars-S" is obtained by placing a 10 tank-car block at each end of the train. "20 Cars-S" causes less contamination only at downwind distances of less than 180 meters. This is because the people who are "too close" to the hazmat-middle of "20 Cars-S" are exposed only to the 10 tank-car block at the back of the train. Given that the train is 612 meters long, the peak concentrate level at 306 meters from *M* is clearly due to the 10 tank-car block at the front of the train. Note that the area within 180 meters of *M* is extremely vulnerable to changes in wind direction. Figure 4 shows that *blocking* hazmat railcars, as in "20 Cars", imposes less transport risk as one moves away from the train.

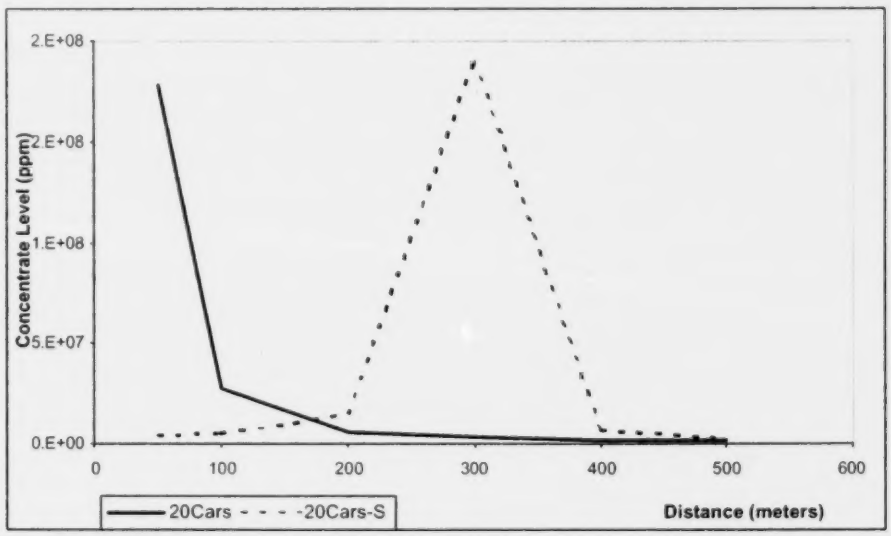

Figure 4: Impact of the positioning of hazmat railcars in the train

Perhaps a more important question is "How does the impact area vary with the number of railcars?" To address this, we assume the hazmat railcars are blocked. Figure 5 depicts the

maximum concentrate levels as a function of distance for 30-railcar, 68-railcar and 120-railcar hazmat blocks.

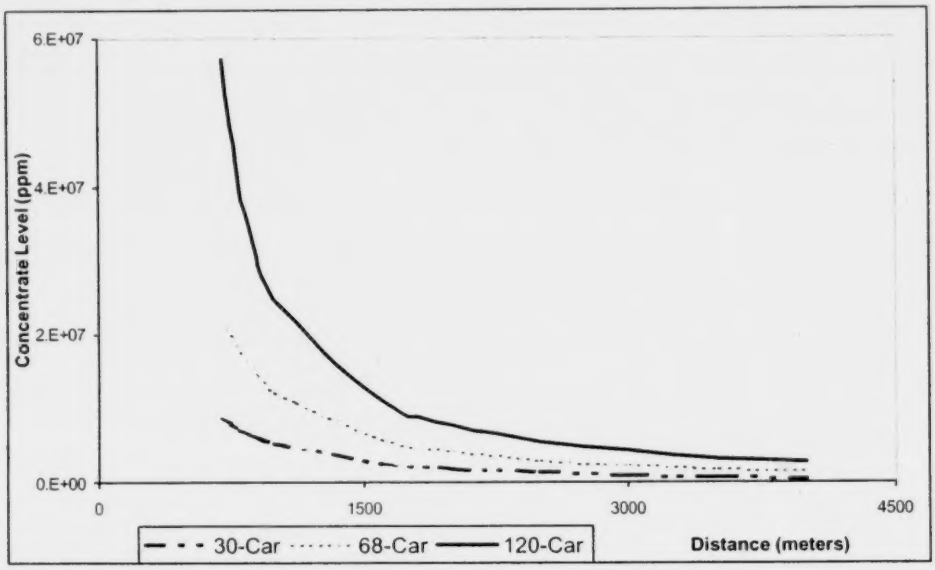

Figure 5: Impact of increasing the number of propane tank-cars

As expected, concentration curve shifts upward as the number of hazmat railcars increases. Consequently, the curve associated with 68 railcars lies within the area defined by the 30-railcar and 120-railcar shipments. At points closer to the train, contaminate accumulates at a higher pace than the increase in the number of hazmat railcars. At 1,000 meters, for example, the concentrate level due to 120 railcars is 4.7 times that of 30 railcars. Figure 5 also shows that the threshold distance for any concentrate level increases with the number of hazmat railcars, although at a slower pace. For example, the threshold distance for 2,500,000 ppm is 1,675 meters for 30 railcars and 4,307 meters for 120 railcars (i.e., the threshold distance increases only 157% when the number of hazmat railcars is quadrupled). Nonetheless, this brings previously unexposed people into the impact area.

The above observations point out a conflict of interest between the residents nearby railroads and those who live far from the tracks. Clearly, the latter group would prefer shorter hazmat railcar blocks, which would not expose them to any transport risk. Once people are

exposed to the possibility of a certain undesirable consequence, however, they would prefer longer hazmat railcar blocks as long as a more severe consequence is not imposed as a result. Because, this reduces the number of times they are exposed. Thus, shipping fewer trains with larger amounts of hazmats can be considered more equitable, since transport risk is spread over a larger populace.

4. Approximating the Maximum Concentration Level

We devised a practical method to estimate the maximum concentration level. For most IDLH levels, there is a substantial overlap among the Gaussian plume footprints caused by multiple railcars of a train. This is because length of a railcar is significantly less than cross-length of a typical footprint. Thus, we can use the following as an approximation for (3):

$$\overline{C}_n(x) = n \times \frac{Q}{\pi u a c x^b x^d} \qquad (4)$$

This amounts to assuming that all the hazardous cargo is located at the hazmat-middle of the train. In the remainder of this section, we show that (4) is not only reliable for estimating the threshold distances, but also robust in terms of train make-up.

Threshold Distance	30 railcars		68 railcars		120 railcars	
	Max	*Approx.*	*Max*	*Approx.*	*Max*	*Approx.*
Severe Zone	*1238*	*1228*	*2041*	*2009*	*3015*	*2977*
Non-Severe Zone	*4466*	*4464*	*7788*	*7783*	*11518*	*11507*

Table 1: Threshold distances (in meters) for Propane as a function of n

Table 1 depicts the threshold distances for 30-railcar, 68-railcar and 120-railcar propane blocks. For each hazmat block, "Max" is calculated via (3) and "Approx" is calculated using (4). The approximate model estimates the threshold distances, at which propane IDLH levels are attained, with an error margin of 1%. The approximate concentrate level shifts upward proportionately to the number of hazmat railcars. The percent increase in the actual concentrate level, however, is more than the percent increase in n at points close to the train. Consequently, accuracy of (4) increases with distance and decreases with the number of hazmat railcars. At 1,000 meters, for example, the approximation errors associated with the severe zone for 30 and

68 propane cars are 1.14% and 7.11%, respectively. These errors reduce to 0.45% and 3.64% at 1,600 meters from hazmat-middle of the train. The approximation errors close to the train are inconsequential since the concentrate levels are very high, making a severe consequence almost certain.

In order to analyze robustness of the approximate model with respect to positioning of the hazmat railcars in a train, we considered three cases: 5, 11, and 21 propane tank-cars in a train with 68 railcars. For each case, 100 train make-ups were generated by randomly positioning the hazardous cargo among the 68 railcars. Table 2 shows the (statistics associated with) non-severe threshold distances as well as the approximations provided by (4). Given n, (4) estimates the same distance for all random train make-ups, since all hazmat is aggregated at the hazmat-middle. The exact calculation of total concentrate level, however, needs to incorporate the actual distance to each hazmat railcar. To illustrate this, consider a train make-up with hazardous cargo in the 5^{th}, 11^{th}, 15^{th}, 37^{th} and 68^{th} railcars. The hazmat-middle, in this example, is the 15^{th} railcar. The hazmat-middle will remain the same if the hazardous cargo in the last railcar was moved to the 38^{th} railcar, whereas the toxicity level at downwind distances from the train's reference point i.e., the 15^{th} railcar, will increase as a result. Thus, Table 2 depicts the average threshold distances of 100 random train make-ups for each of the three cases.

Threshold Distance	5 Hazmat Railcars	11 Hazmat Railcars	21 Hazmat Railcars
Approximate	*1341*	*2204*	*3417*
Average	*1366*	*2213*	*3422*
Std. Dev.	*60*	*41*	*33*

Table 2: Threshold distances (in meters) under random positioning of hazmat railcars

The approximation error is within 2% for all three cases. This enables us to surmise that the approximate model remains effective under uncertainty regarding the positioning of hazmat railcars in the train. Also, the approximate model performs better as the number of hazmat railcars increases. This can be explained by the reduction in variance of the threshold distance as hazardous content of the train increases. The distances in Table 2 are calculated at downwind locations assuming that the train is traveling east, as in Figure 2. If the train is traveling in the opposite direction, the average threshold distances will be slightly different, whereas the approximate distance will remain the same.

5. Assessment of the "Ultra-train" Shipments

In this Section, we present an application of the proposed methodology in the province of Quebec, Canada. Everyday, CN (Canadian National) runs a train from Ultramar's refinery near Quebec City to its terminal in Montreal. This 68 tank-car train, which CN calls the "Ultra-train" is devoted to finished petroleum products such as, gasoline, diesel, jet fuel and propane. Ultra-train uses the CN main-line, which is the southern route in Figure 6a. The public is sensitized to the Ultra-train shipments due to a 1999 accident near Mont-Saint-Hilaire, that killed two CN employees. A popular newspaper [21] pointed out that if the derailment occurred in a residential area, rather than an industrial zone, its impact could have been much worse. Consequently, there is considerable concern with the circuitous nature of the current route in the city of Montreal, which is depicted in Figure 6b.

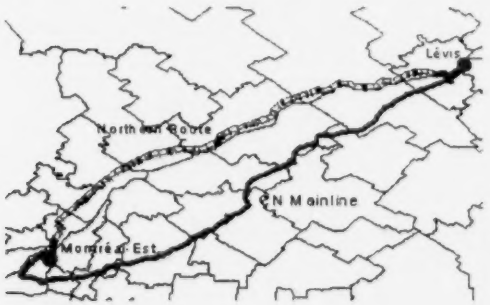

Figure 6a Ultra-train routes through Quebec **Figure 6b:** Ultra-train routes through Montreal

According to a report commissioned by the EPA [22], bulk evaporation is typically quite high for refined petroleum products e.g., 90 to 100 percent for gasoline. The report also suggests that these products can be modeled as neutrally buoyant gasses, although their vapors are heavier than air. The content of Ultra-train varies daily, and the information regarding its cargo is not publicly available. In order to arrive at a conservative estimate of population exposure, we model the entire cargo as a propane shipment. Propane is shipped as a liquefied gas, which becomes airborne immediately after an accidental release. Gasoline, for example, is initially released as a liquid, which results in a spill, and then evaporates gradually. The other model parameters are set as described in Section 2. The capacity of each tank-car is 80 tons.

The aggregate IDLH levels for propane exposure are 4,200,000 ppm and 600,000 ppm for severe and non-severe consequences, respectively [10]. Using our model, the fatality threshold distance for the Ultra-train is 2 kilometers, whereas people within 7.7 kilometers of the railroad are exposed to injury risk[4]. We use ArcView, a popular Geographical Information System, in generating the corresponding exposure zones around the CN main-line. Then, we overlay these zones on the population centers (i.e., the polygons in Figure 6a) and identify the intersection areas. The total number of people in the severe zone is 492,195, whereas the population within the non-severe zone is 986,206. In total, Ultra-train exposes about 1.5 million people to varying degrees of transport risk.

During our analysis of the existing railroad network, we identified two alternative routes for Ultra-Train. The "shortcut link" allows for a detour from the CN main-line via a north turn upon entering the island of Montreal (see Figure 6b), which results in a 16 kilometer reduction in inner-city travel. The "northern route", however, avoids the island of Montreal almost entirely by entering from northeast (see Figure 6a). Using our model, we also assessed the transport risk associated with these two routes. If the shortcut link is used, the number of people in the severe zone will reduce 36% and there will be a 24% reduction in the exposure to non-severe consequences. The use of northern route, however, will result in a 57 % reduction in both fatality and injury exposures. The northern route is only 3.4% longer than the current route, whereas the shortcut link provides a 5.6% reduction in travel distance. The primary reason for CN to continue using its main-line, which has much higher population exposure, is track quality. The company is deterred from using either of the two alternate routes by the significant capital outlay required for track upgrades and installation of monitoring equipment.

The large amount of refined petroleum products shipped through the city of Montreal on a daily basis is a significant concern for the emergency response planners in Quebec. The analysis in Section 3 shows that a reduction in the volume of hazmats will not pay off in term off the resulting decrease in the threshold distance. If the number of tank-cars in Ultra-train is halved, for example, the threshold distance of the current severe zone will decrease only 9%. In this case, CN will have to run two 34 tank-car trains daily in order to satisfy Ultramar's demand. Each shipment exposes 437,176 people to fatality risk, and hence total exposure in the

[4] Following the suggestion in [8], CN uses a single threshold distance of 800 meters in their risk assessment.

severe zone will increase 78% due to the use of 34 tank-car trains. Due to the non-linearity of concentrate curve, the impact is less drastic within the non-severe zone: Threshold distance for injuries decreases 38%, which puts 619,099 people at injury risk and results in a 26% increase in exposure to non-severe consequences. It is interesting to note that emergency response planners are more concerned with the number of people within the exposure zone than the total exposure. Clearly, this amounts to ignoring the number of times an individual is exposed to a certain risk. A common response to hazmat incidents is evacuation of the impact area around the site of accidental release. Reducing the impact area of an accident, through decreasing the volume of hazmat involved, certainly makes emergency response planning easier. Therefore, emergency response planners in Quebec prefer any reduction in the length of Ultra-train despite the associated increase in population exposure.

6. Concluding Remarks

This paper presents a risk assessment methodology for railroad transportation of dangerous goods. Focusing on hazmats that are airborne on release, we represent exposure zone as a function of the volume of hazmat shipped and the make-up of the train. The definition of exposure in terms of concentrate level enables us to model the reduction in transport risk with distance from the railroad. In addressing the multiple release-source nature of train accidents, we propose the use of hazmat-middle of the train as a reference point, which also provides a solid basis for approximating the threshold distances for different consequences. In setting parameters of the model, we adopt a worst-case approach to transport risk. This allows us to incorporate the uncertainty in wind direction by focusing on maximum concentration levels.

The proposed methodology provides valuable insights with regards to the nature of railroad transport risk. Most notably, we point out the conflict of interest among the people living nearby railroad tracks and those who are not in the immediate vicinity. Given a certain amount of hazmat to be shipped, increasing the amount of hazardous cargo on each train would favor the former group. We also establish that, in general, blocking hazmat railcars would reduce population exposure. Although we assumed neutral atmospheric stability in this paper, additional computational experiments shows that the overall results do not change under other stability conditions. Application of the methodology for assessment of Ultra-train's transport risk enabled us to validate our insights.

There are a number of future research directions. First, the proposed methodology can be extended to incorporate accident probabilities. This requires a solid understanding of how accident probability varies with train length. Since train accidents are very rare events, validation of such a probabilistic model against accident data constitutes a formidable challenge. Second, the development of a methodology to analyze the cost-risk trade off in the context of railroad shipments would be a significant contribution. This would certainly facilitate the negotiation between the railroad company and regulator towards mitigating the public and environmental risks associated with trains. Finally, the increasing popularity of multimodal transportation calls for the development of an integrated risk assessment methodology that incorporates both railroad and highway shipments

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